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GENERATION OF A VORTEX RING BY THE SUDDEN COMBUSTION OF GAS

Anthony R. Kriebel

URS Research Company

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Technical Report

GENERATION OF A VORTEX RING BY THE SUDDEN COMBUSTION OF GAS

by

A. R. Kriebel, Sc. D.

prepared for

OFFICE OF NAVAL RESEARCH
Department of the Navy
Arlington, Virginia 22217

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A total of 52 such tests were run with various amounts of propane. The gas mixtures ignited for 48 of these tests. Only slow speed vortex rings were generated, however, and these occurred only when the volume of burned gas was much greater than required to fill the cylinder. When less gas was burned, the air which was expelled from the cup did not form a vortex ring and propagate away from the cup. The reason for this is apparently that the mixing of the propane and air was so poor that the combustion and expansion was too slow to impart enough kinetic energy to the expelled gases.

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Tests were run to investigate the feasibility of generating air vortex rings by the rapid combustion and expansion of propane-air mixtures near the bottom of a short cylinder to drive the air out of the cylinder.

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CONTENTS

Section 1
INTRODUCTION

This is a report on a very limited series of experiments designed to examine the feasibility of generating air vortex rings simply and inexpensively by the rapid combustion or explosion of a mixture of a detonable gas and air in a suitable enclosure.

The use envisaged for such a vortex generator was as a means for applying an impulse loading to a large structure without physical contact. The resonant frequency and frictional damping of the structure could then be determined from its vibrational response by use of a commercially available laser interferometer. In this case, only very small loadings, such as those that would result from the impaction of air vortex rings, are required since structural displacements of the order of one wavelength of light can be measured. The impulsive air loading by air vortex rings would have several attractive features. The loading could be directed and localized over a few square feet of surface area; it could be applied to areas which are difficult to reach for attachment of mechanical loading devices; and finally, the impulsive air loadings might be generated repetitively at a frequency which is variable through the resonant frequencies of the structure.

Previous experiments have shown that underwater vortex rings can be generated by explosions in containers shaped like cups, or short gun barrels, about one diameter long (Ref. 1). The formation of air vortex rings at the open end of a shock tube has also been demonstrated (Ref. 2). Therefore, in this experimental series the enclosure used was a cup-like cylinder about one diameter long, and the attempt was made to cause the detonable gas-air mixture to operate like a shock tube by injecting the gas (propane was used) near the base of the cup just prior to its ignition. The burning gases expanded and drove the remaining air out the cup as in an ordinary shock tube with a short expansion chamber.

In this case, no moving parts (except for a gas valve) are required so that repeated firing is much simpler to accomplish than with a normal shock tube in which diaphrams must be burst and replaced.

The basic configuration of the vortex generator used in this brief program is shown in Figure 1. A 55-gallon steel barrel was partially filled with sand so that the empty portion formed a cup with both the diameter and length equal to 22 inches. The top edge of the barrel was cut off and ground sharp. If the bottom seventh of the cup is filled with a mixture of propane and air (6 percent by weight), then upon combustion this layer of gas will expand until it just fills the barrel, according to the estimates in Appendix A. Upon being suddenly expelled from the barrel, the air above the expanded layer forms a vortex ring from outside the sharp lip of the barrel which then propagates away from the barrel.

The remainder of this report is a description of the test apparatus, test results, and supporting calculations.

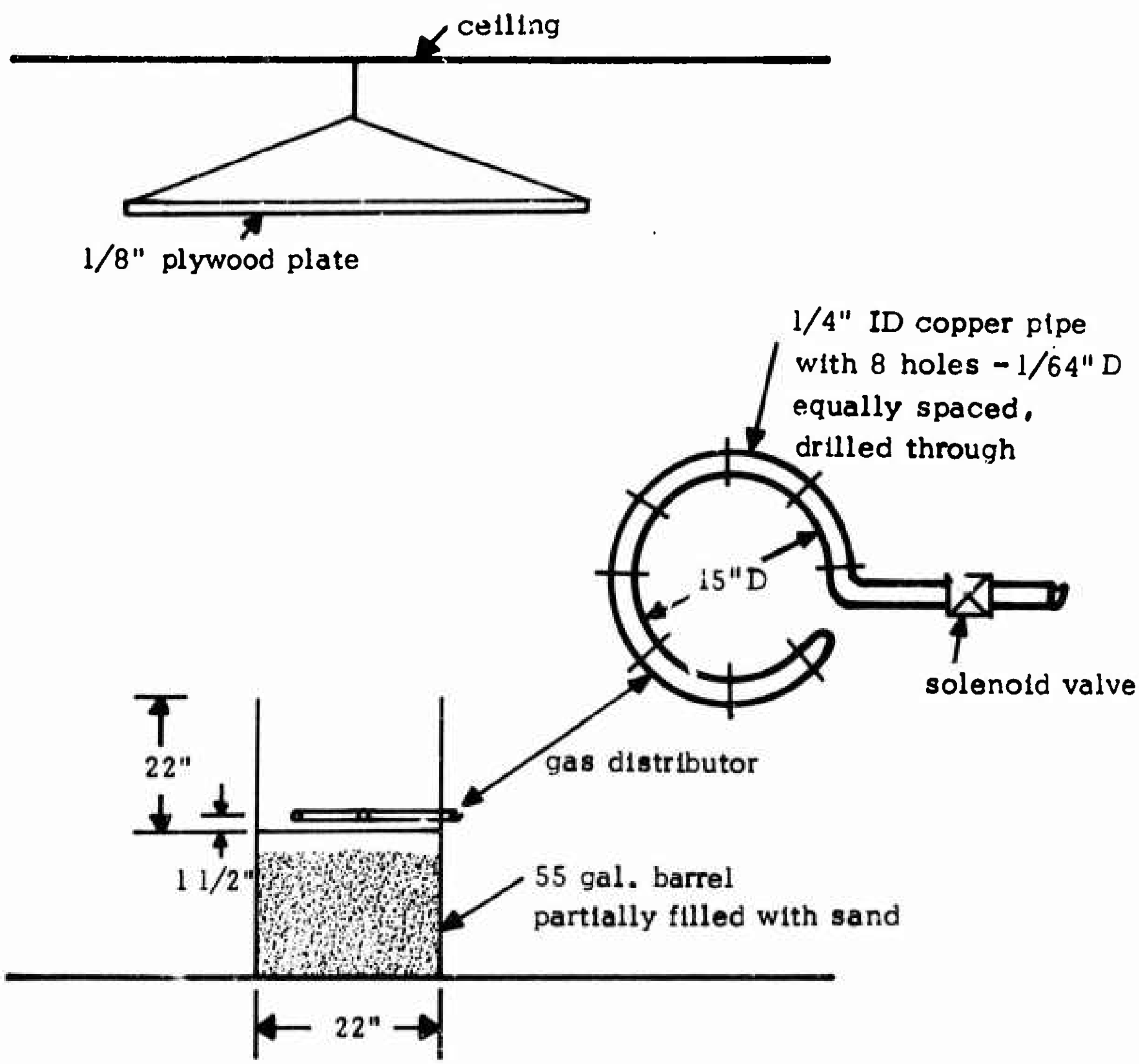


Fig. 1 Configuration of Air Vortex Generator and First Gas Distributor

Section 2
EXPERIMENTAL PROGRAM

Propane gas was injected near the bottom of the air in the barrel by a distributor ring as shown in Figure 1. This ring consisted of a 1/4-inch ID copper pipe bent into a 15-inch diameter circle so that the barrel volume inside the ring was nearly equal to that outside. The ring was located 1-1/2 inch above the bottom of the air volume in the middle of the desired 3-inch layer of combustible mixture. The propane gas was injected through 16 holes equally spaced around the ring as shown in Figure 1 after it was released by a quick-opening solenoid valve from a tank partially filled with liquid propane. The tank pressure was equal to the vapor pressure of propane, or 124 psig.

Two gas distributors were used. In the first, the 16 holes were 1/64 inch in diameter. From the gas flow rate estimated in Appendix A, it would take 0.7 second to inject enough propane for complete combustion with the bottom 3-inch layer of air in the barrel, and 4.8 seconds for complete combustion with all the air in the barrel.

To reduce the flow rate and change the mixing properties of the propane jets issuing from the distributor, the 16 holes in the distributor pipe were enlarged to 1/32-inch diameter, and a single orifice plate with a hole diameter of 0.026 inch was placed in the pipe just outside the barrel. The total area of the 16 holes was then 4 x 0.00307 = 0.012 in.^{2}, and the area of the control orifice was a 0.00053 in.^{2}. The estimated flow rate is then reduced by the factor .00307/.00053 = 5.8. Thus, for the second distributor the estimated propane flow durations are 4 seconds for complete combustion with the bottom 3-inch layer of air, and 28 seconds for all the air.

The propane flow durations were controlled by an automatic timer which operated the solenoid valve, and the flow duration was measured for each test

with a stop watch. Just after the propane was injected, it was ignited by a sparkplug located at the center of the distributor ring.

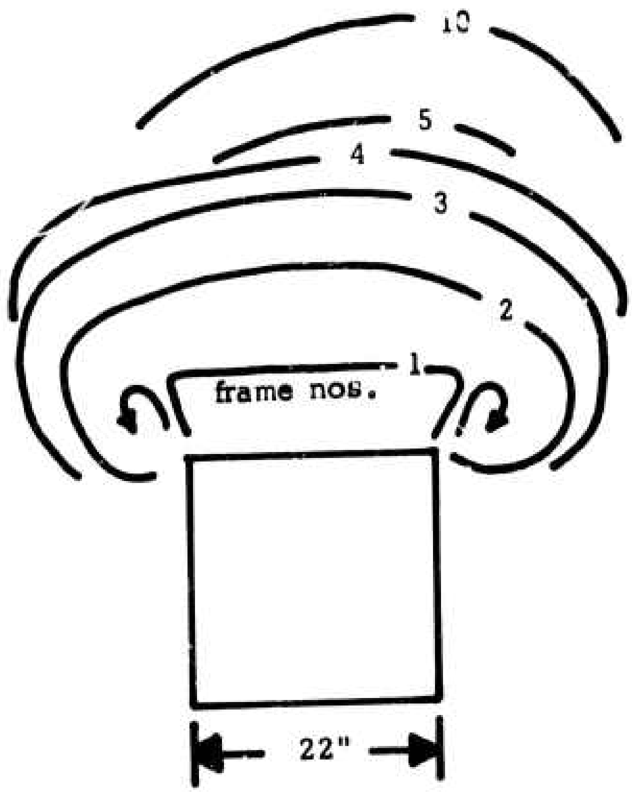
A smoke generator was used to produce smoke above the barrel, and movies were taken at 64 frames/second looking sideward to show the top of the barrel, the plywood plate overhead, and the region between (Figure 1).

Section 3
TEST RESULTS

A series of 36 tests were run with the first gas distributor and with the propane flow duration varied from 1 to 5-1/4 seconds. For five of the 36 tests, the propane flow duration was between 1 and 2 seconds, and there was only a minimal indication of the air expelled from the barrel as a slight disturbance of the smoke column above the barrel, and there was almost no evidence of vortex ring formation. However, for the remainder of the tests where the flow duration exceeded 2 seconds, a flame front emanated from the barrel which was distinctly visible in the first few frames of the movies of the tests. The movies of these later tests also showed a distinct disturbance of the plywood plate which was hung from the ceiling above the barrel, as indicated in Figure 1. This plate was 4 ft x 4 ft x 1/8 in. thick, and it weighed about six pounds.

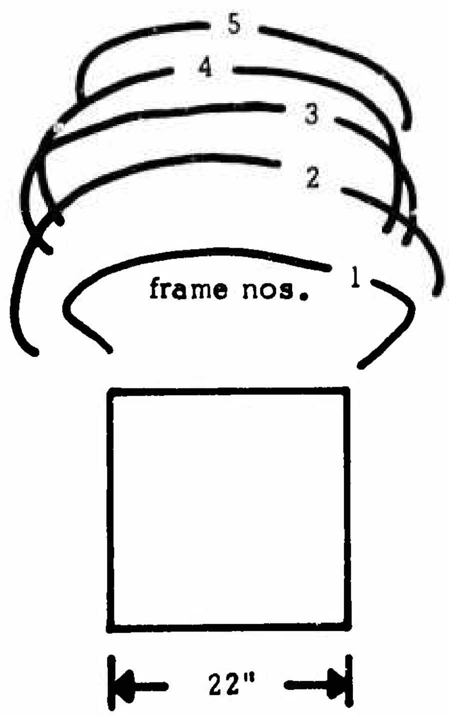
Figures 2 through 8 show the shape of the flame front versus time for several of these tests. (The squares in these figures indicate the side view of the cylindrical air volume.)

It can be seen in Figures 2 through 8 that the flame fronts were roughly comparable for all the tests where the propane flow duration varied from 2 to 5-1/4 seconds. The flame front and the burning gas within it became invisible after the last movie frames indicated. The vertical speed of the flame front between the last two positions shown in Figures 2 through 8 varies between 10 and 25 fps, and there is a distinct decrease in speed as the gas volume propagates away from the barrel. There was a swirling motion within the volume of burning gas which was apparent in the first few movie frames. Although the swirling motion constituted a vortex ring, the vorticity did not appear to be confined within a sharply defined core.



64 frames/sec.
propane flow for 2 sec.

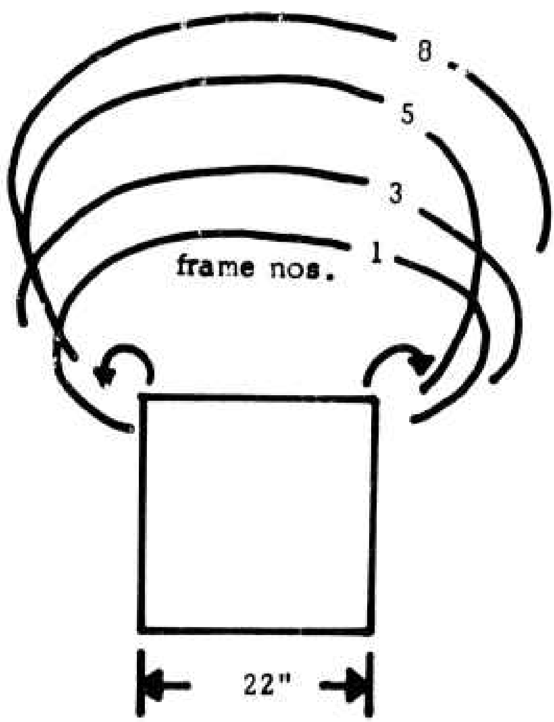
Fig. 2 Flame Front vs. Time



64 frames/sec.

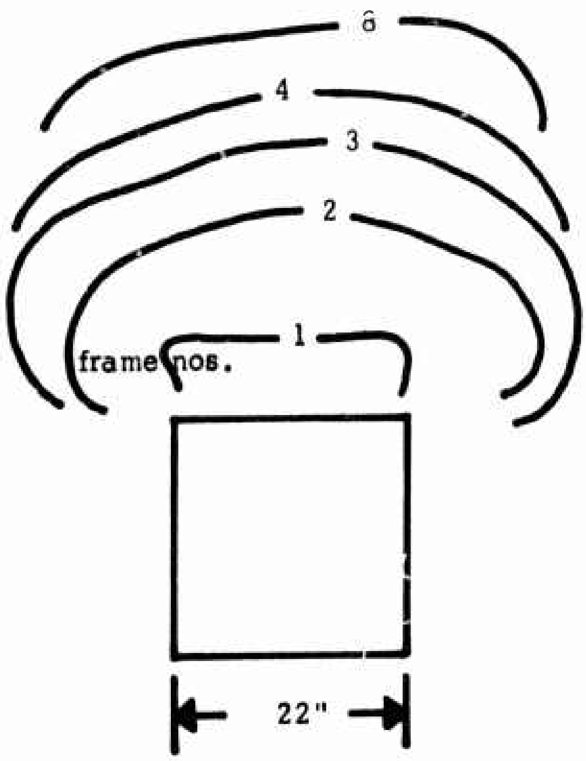
propane flow for 2 sec.

Fig. 3 Flame Front vs. Time



64 frames/sec.
propane flow for 3 sec.

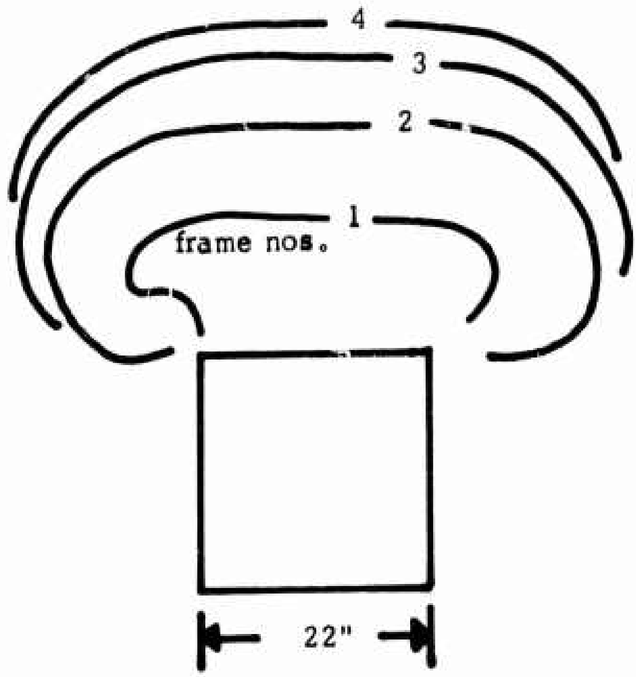
Fig. 4 Flame Front vs. Time



64 frames/sec.

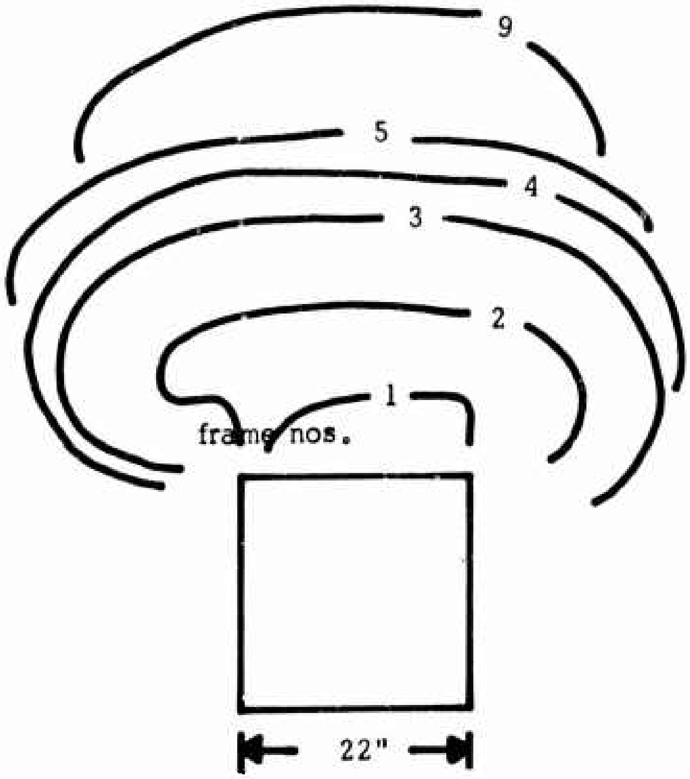
propane flow for 4 1/4 sec.

Fig. 5 Flame Front vs. Time



64 frames/sec.
propane flow for 4 3/4 sec.

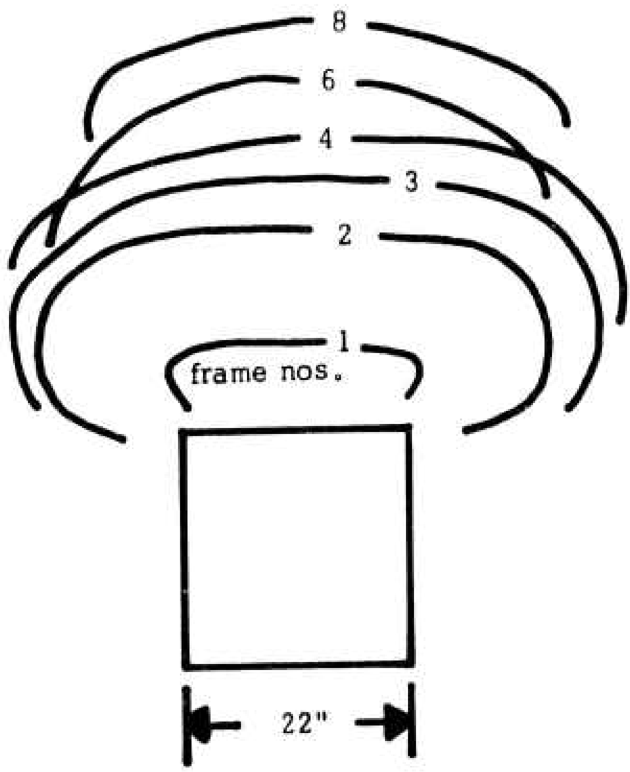
Fig. 6 Flame Front vs. Time



64 frames/sec.

propane flow for 5 sec.

Fig. 7 Flame Front vs. Time



64 frames/sec.

propane flow for 5 1/4 sec.

Fig. 8 Flame Front vs. Time

The last three figures correspond qualitatively with the estimated propane flow duration of 4.8 seconds required for complete combustion of all the air in the barrel, followed by a 7 to 1 expansion of the burned gasses. However, the combustion rate was clearly very slow since the burning persisted until the gasses had fully expanded out of the barrel. The volume of burned gas does not increase in proportion with the amount of propane in Figures 2 through 8, which indicates that complete combustion did not occur for all the tests.

Another indication that long flow durations led to poor combustion is provided by the test results for the second propane distributor. Sixteen tests were run with this distributor with the propane flow duration ranging between 2 and 10 and with at least two tests at each duration. For the longest flow duration, the amount of propane should have been the same as for 1.7 seconds flow duration with the first distributor configuration. For four of the 16 tests, the propane did not ignite the first time (with the flow durations equal to 2, 4, 6, and 8 seconds). For the remainder of the tests, the visible and audible indications of combustion were weaker than for the first propane distributor, even when the amounts of propane were equivalent. There was never a visible flame front outside the barrel, and the smoke tracer indicated only a slight outflow from the barrel. There was never a noticeable disturbance of the plywood plate above the barrel.

In summary, with the 48 gas mixtures that ignited (of the 52 used), only slow speed vortex rings were generated (fast ones had been expected), and these occurred only when the volume of burned gas was much greater than required to fill the barrel. When less gas was burned, the air which was expelled from the cap did not even form a vortex ring.

Section 4
DISCUSSION

The foregoing test results indicate that the rate of combustion of propane in air was too slow for both propane distributors which were tried. Diffuse vortex rings were generated when the flow duration was greater than 2 seconds for the first propane distributor. For the 2-second tests, it is estimated that the amount of propane should have burned completely with half of the air in the barrel, and the burned gasses should have expanded to about 3-1/2 times the barrel volume.

Although the gasses appeared to expand to roughly this volume (in Figures 2 and 3), they continued to burn until they were fully expanded. This indicates that the propane distributor did not provide adequate mixing and that the combustion rate was too slow to expel the gasses from the barrel rapidly. The combustion rate must be greatly increased to expel the gasses rapidly enough to generate a powerful concentrated vortex core outside the lip of the barrel so that the vortex ring will propagate much faster with greater momentum as desired.

The second configuration was adopted to slow the flow rate, thereby (hopefully) improving propane/air mixing, and increasing combustion rates. It would appear, however, that better results might have been obtained by <u>increasing</u> flow rate; poorer combustion rates were experienced in the second configuration than in the first when equal volumes of propane were injected.

The best way to increase the chemical reaction rate drastically is probably to inject a detonable mixture of propane and air (or propane and oxygen) through a central hole in the bottom of the air volume and to detonate the mixture. A hemispherical volume of mixture is probably best and this might be achieved either by slowly flowing the mixture out through a porous, hemispherical cap over the injection port, or by inflating a rubber membrane to form a hemispherical bubble of detonable gas at the bottom of the barrel.

The latter method might be tried first to obtain data on vortex generation, and then after sufficiently powerful vortices are generated, the membrane might be replaced by the porous cap.

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Appendix
CALCULATED RESULTS

The following calculations provide estimates of the propane flow rate and expansion upon combustion based upon data obtained from Ref. 3.

The volume of the top portion of the barrel which was not filled by sand (22 in. D x 22 in. L) was 8359 in.^{3} or 4.84 ft^3, and the corresponding weight of air was 0.0765 x 4.84 = 0.370 lb. Propane was chosen as the propellant over butane because of its greater availability since the following properties of the two gasses are so similar. At normal pressure and temperature the density of propane is 1.52 times that of air (and for butane 2.01 times). The high heating values are nearly the same for the two gasses, 21,560 BTU/lb for propane and 21,180 for butane. The maximum flame temperatures are also nearly equal, 3595°F for propane and 3615°F for butane.

For complete combustion of propane 15.58 lb of air are required per lb of propane. The estimated temperature rise of the products of combustion for propane is:

$$\Delta T = (\Delta H/C\rho)\left(\frac{\text{lb of propane}}{\text{lb of products}}\right)$$

$$= (21{,}560/.404)\ (1/16.58)$$

$$= 3219^\circ F$$

so that their final temperature is

$$T = 3289^\circ F = 3749^\circ R$$

It is estimated that the pressure of the products remains nearly constant during combustion so that their density is reduced by the temperature ratio, 3749/530 = 7.07. Therefore, as a first approximation, it is estimated that the bottom seventh of the air volume will expand to fill the cup it burns

completely after the required amount of propane is mixed into it. The correct amount of propane in the bottom seventh of the cup for complete combustion of the layer is .370/(15.58 x 7) = 0.029 ft^3 = 0.0034 lb.

If the entire cup is filled with a propane-air mixture for complete combustion, the amount of propane is 0.0238 lb and the corresponding heat release is:

$$21,560 \times 0.0238 = 513 \text{ BTU} = 40 \times 10^4 \text{ ft-lb}$$

For the same release of energy the corresponding TNT charge weight is:

$$Y = 40 \times 10^4/1.43 \times 10^6 = 0.28 \text{ lb}$$

Thus, the tests were performed in an appropriate explosion test site.

The estimated expansion ratio neglected the work done by the gas layer as it expands to fill the cup. This amount of work is roughly equal to the volume swept out times the atmospheric pressure, or 9,000 ft-lb compared with the heat release of 400,000/7 = 57,000 ft-lb. If all the air in the cup is driven out at a speed of 100 ft/sec, the corresponding kinetic energy is only 50 ft-lb. Since the measured speed is much less than this, it is evident that very little of the heat released is used to propel the mass of air associated with the vortex ring, and that nearly all this energy is used to heat the products of combustion as assumed.

For the first propane distributor (Figure 1) the mass flow rate of propane through 16 holes with diameter equal to 1/64 in. from a tank pressure of 124 psig is estimated as follows. The area of one hole is 1.92 x 10^{-4} $in.^2$, and for all 16 holes the flow area is 30.7 x 10^{-4} $in.^2$. Since the tank pressure is well in excess of that required for choked flow (with sonic velocity through the holes) the ideal flow rate, w, is given by

$$w \text{ (lb/sec)} = AP \left[(gk/RT) \ (2/(k+1)^{k+1/(k-1)} \right]^{1/2}$$

$$= 0.01115$$

where

A = orifice area = 30.7×10^{-4} in.^{2}

P = tank pressure = 139 psia

T = tank temperature = 530°R

g = gravitational constant = 32.2 ft/sec^2

R = gas constant for propane
= 1545/44.06 = 35.1 ft/°R

k = ratio of specific heats for propane
= 1.125

The discharge coefficient for the holes is estimated to be about 1/2, so that the actual estimated flow rate is 0.005 lb/sec. Therefore, to obtain the amount of propane for complete combustion with the bottom seventh of the air in the cup the flow duration is .0034/.005 = 0.7 sec, and for all the air in the cup the flow duration is .0238/.005 = 4.8 sec.